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Age-Related Delay in Reduced Accessibility of Refreshed Items

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Previously, we demonstrated that in young adults, briefly thinking of (i.e., *refreshing*) a just-seen word impairs immediate (100-ms delay) perceptual processing of the word, relative to words seen but not refreshed. We suggested that such reflective-induced inhibition biases attention toward new information. Here, we investigated whether reduced accessibility of refreshed targets dissipates with a longer delay and whether older adults would show a smaller and/or delayed effect compared with young adults. Young adult and older adult participants saw 2 words, followed by a cue to refresh one of these words. After either a 100-ms or 500-ms delay, participants read a word that was the refreshed word (refreshed probe), the nonrefreshed word (nonrefreshed probe), or a new word (novel probe). Young adults were slower to read refreshed probes than nonrefreshed probes at the 100-ms, but not the 500-ms, delay. Conversely, older adults were slower to read refreshed probes than nonrefreshed probes at the 500-ms, but not the 100-ms, delay. The delayed slowing of responses to refreshed probes was primarily observed in older-old adults (75+ years). A delay in suppressing the target of refreshing may disrupt the fluidity with which attention can be shifted to a new target. Importantly, a long-term memory benefit of refreshing was observed for both ages and delays. These results suggest that a full characterization of age-related memory deficits should consider the time course of effects and how specific component cognitive processes affect both working and long-term memory.

Keywords: refreshing, reflective attention, aging, inhibition, working memory

Aging is associated with cognitive deficits in a number of domains (e.g., Park et al., 2002). One important characteristic of cognitive aging is greater vulnerability to interference from distracting information (e.g., Anderson, Healey, Hasher, & Peterson, 2016; Andrés, Guerrini, Phillips, & Perfect, 2008; Connelly, Hasher, & Zacks, 1991; Healey, Hasher, & Campbell, 2013; Higgins & Johnson, 2009; Jonides et al., 2000; Lustig, May, & Hasher, 2001; Raye, Mitchell, Reeder, Greene, & Johnson, 2008; Weeks & Hasher, 2014; Yi & Friedman, 2014; for a review, see Lustig & Jantz, 2015). For example, older adults are more vulnerable than young adults to proactive (e.g., Jonides et al., 2000; Lustig et al., 2001; Yi & Friedman, 2014) and semantic (Higgins & Johnson, 2009) interference in working memory. Similarly, having more items active in working memory (three just-seen words vs. one just-seen word) disproportionately slows older adults' response times to read a word (Raye et al., 2008). Compared with young adults, older adults are differentially slower to read text when it is interspersed with distracting words (e.g., words presented in a to-be-ignored font) than when it is not (Connelly et al., 1991). The idea that age-related vulnerability to interference reflects a general deficit in neurocognitive inhibitory mechanisms that operate to suppress competition from distracting information (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988) has received support from behavioral (e.g., Healey, Ngo, & Hasher, 2014), electroencephalogram (EEG; e.g., Haring et al., 2013; Yi & Friedman, 2014), and functional magnetic resonance imaging (fMRI; e.g., Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Mitchell, Johnson, Higgins, & Johnson, 2010) studies. For example, when briefly and simultaneously shown a face and scene and then immediately cued to think of the face, young but not older adults showed suppression

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A subset of the older adult data in the current study was included previously in a poster presentation at the 2011 Annual Meeting of the Psychonomic Society, Seattle, Washington. The young adult data have not been presented elsewhere. Data are available at the following link: https://osf.io/zb9qx/. This research was supported by a National Institute of Mental Health Grant (MH092953) awarded to Marcia K. Johnson. We thank Kelly Durbin, Rafay Khan, Jatnna Rivas, and Maxim Tingaud for assistance with data analysis; Maria Robbins, Irena Curanovic, and Amber Aparicio for assistance with data collection; and Kristjana Hysaj, Maria Robbins, Stephanie Stradling, Joseph Tesler, and Maxim Tinguad for assistance with literature searches and proofreading.

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of scene-specific activation in the parahippocampal area (Mitchell et al., 2010).

Recent neurophysiological research also suggests that it is important to consider the time course of inhibition. Some studies have found that inhibitory mechanisms in older adults may be impaired during early processing of distracting information but then are relatively preserved later on (Gazzaley et al., 2008; Yi & Friedman, 2014; also see Jost, Bryck, Vogel, & Mayr, 2011; Schwarzkopp, Mayr, & Jost, 2016). For example, in a working-memory task used by Gazzaley et al., young and older adults were successively shown two faces and two scenes in random order and cued in advance to either remember the faces, remember the scenes, or simply view the items. Examining EEG signals during the first 200 ms of the encoding sequence, Gazzaley et al. observed that, relative to baseline, both young and older adults showed greater amplitudes of face-specific signals (N1 and P1) when attending to faces, but only the young adults also showed smaller responses of the N1 and P1 when ignoring faces. However, alpha power measured between 500 and 650 ms poststimulus showed enhancement and suppression relative to the baseline in both age groups. Hence, a comprehensive understanding of age-related changes in inhibition should take into account the time course over which inhibitory mechanisms operate.

One limitation of prior studies demonstrating delayed inhibition of interference in older adults is that the tasks used are relatively complex, preventing conclusions about what specifically led to the delay in inhibition. For example, in the Gazzaley et al. (2008) study, participants were simultaneously perceptually attending to and/or ignoring stimuli currently on the screen, as well as reflectively attending to and/or ignoring representations of previously viewed stimuli currently active in working memory. The delay in inhibition obtained could have arisen from age-related deficits in perceptual attention, reflective attention, or both (e.g., Mitchell et al., 2010). When prior tasks required only reflective attention to items active in working memory (e.g., Yi & Friedman, 2014), multiple items had to be maintained over a relatively long interval (2,000 ms in Yi & Friedman, 2014), which likely required multiple reflective attention processes (e.g., *refreshing* and *rehearsing*; Chun & Johnson, 2011; Johnson & Hirst, 1993). Hence, the delay in inhibition may be associated with selectively *refreshing* a single item within working memory, *rehearsing* multiple items in a continuous loop, or both (for evidence concerning the distinction between refreshing and rehearsing, see, e.g., Camos, Mora, & Oberauer, 2011; Raye, Johnson, Mitchell, Greene, & Johnson, 2007).

In the current study, we examined whether inhibition associated with a simple act of reflective attention is impaired in aging. To do so, we built on our previous finding in young adults of a reduced accessibility for item information that had just been the target of a simple act of reflective attention, *refreshing* (Johnson et al., 2013). Young adults saw two words on the screen (one above, one below center), followed by a central arrow pointing either up or down. Participants were instructed to think of (i.e., *refresh*) the word that was just in the location indicated by the cue and to say that word aloud. After a brief (100-ms) delay, a probe word appeared in the center of the screen, which participants read aloud. This word was either the refreshed word from the initial display, the nonrefreshed word from the initial display, or a novel word. We found that probe response times were slower for refreshed words than nonrefreshed words, suggesting that immediate access to the refreshed item was inhibited. In a comparison condition in which participants merely saw a word repeated and read it aloud (instead of refreshing it), there was no slowing of response times to the repeated-word probe, suggesting that this inhibition resulted specifically from the act of reflectively attending to the target, not from perceptually processing it or speaking it. Thus, this task provides evidence for inhibition associated with a specific, reflective component process of cognition. Interestingly, long-term memory was better for refreshed compared with nonrefreshed words, suggesting that the inhibitory effect was short-lived and did not offset the long-term benefit of refreshing a target typically seen in young adults (Johnson, Reeder, Raye, & Mitchell, 2002). Here we tested whether such long-term memory benefits of refreshing would be observed even in the presence of age differences in the inhibition of refreshed targets.

Thus, in the current study, we examined whether older adults would show a similar inhibitory effect from a brief act of reflective attention within working memory, using a similar paradigm to that of Johnson et al. (2013). To investigate potential age-related differences in the time course of inhibition of the refreshed item, we included the 100-ms-delay condition used by Johnson et al. and added a 500-ms-delay condition. For young adults, we expected to replicate our previous finding of refresh-induced inhibition at the 100-ms delay. Given that the young adults in our previous study showed a long-term memory benefit from refreshing, suggesting any suppression/inhibitory effect was transient, we predicted that the inhibitory effect would have dissipated by 500 ms. We chose 500 ms as the longer delay based on findings that older adults show similar neurophysiological responses to interference in working-memory tasks compared with young adults starting at delays of 500–600 ms (Gazzaley et al., 2008; Jost et al., 2011; Yi & Friedman, 2014). As such, in older adults, we expected to observe refresh-induced inhibition in the 500-ms, but not the 100-ms, delay. Of course, the failure of older adults to show evidence of inhibition even at the longer delay would suggest a more severe disruption of inhibition of an item that was just in the focus of reflective attention. Additionally, we investigated whether the long-term memory benefits from refreshing observed by Johnson et al. would replicate in young adults at the 100-ms delay and extend to young adults in the 500-ms delay and older adults at either or both delays.

Multiple factors contribute to the changes in cognition associated with aging, and many cognitive changes are most pronounced in advanced old age (e.g., Braver & Barch, 2002; Buckner, 2004). Thus, as a post hoc analysis, in addition to an overall comparison between young and older adults, we also split our older group into younger-old (<75 years) and older-old (75+ years) subgroups and compared young adult participants separately to each of those subgroups with respect to the short- and long-term effects of refreshing.

Method

Participants

Participants were 72 older adults recruited from the New Haven community and 72 young adults recruited from Yale University's student body. Participants were randomly assigned to a delay group (100 or 500 ms), with the restriction that the age distribution in the two groups should be roughly comparable. Data from six participants were excluded for the following reasons: two older adults from the 100-ms-delay group who reported a history of stroke on a posttask questionnaire; one older adult in the 500-ms-delay group whose mean response time was greater than 3 standard deviations from the overall mean for both age groups; one young adult from the 100-ms-delay group and two from the 500-ms-delay group for whom English was not their first language and who made mistakes on a majority of trials. The 138 remaining participants reported no history of neurological impairment or psychiatric illness and had normal or corrected-to-normal vision. Participants received financial compensation for their participation. This study was approved by the Yale University Human Subjects Committee.

Young adults in the two delay conditions did not differ in age, $t(67) = -.59$, $p = .55$; years of education, $t(50) = -.29$, $p = .78$; or verbal scores, $t(59.56) = 1.85$, $p = .07$ (see Table 1 for descriptive statistics of all demographic variables). Older adults in the two delay conditions did not differ significantly in age, $t(67) = -.13$, $p = .90$; years of education, $t(67) = -1.07$, $p = .29$; verbal ability, $t(67) = -1.16$, $p = .25$; or cognitive status as assessed by the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975), $t(58.31) = 1.34$, $p = .19$.

To explore potential age differences within the older group, we divided them into two subgroups, "younger-old" (aged 60–74 years) and "older-old" (aged 75 years and older; see Table 1). The younger-old participants in the two delay conditions did not differ in age, $t(28) = .06$, $p = .96$; years of education, $t(28) = -1.72$, $p = .10$; cognitive status, $t(28) = .85$, $p = .40$; or verbal scores, $t(28) = -.26$, $p = .79$. The older-old participants in the two delay conditions did not differ in age, $t(37) = .62$, $p = .54$; years of education, $t(37) = .21$, $p = .83$; verbal ability, $t(37) = -1.27$, $p = .21$; or cognitive status, $t(37) = .90$, $p = .38$.

Materials and Design

Main task. The same materials and design from Experiment 1 of Johnson et al. (2013) were used. Words were nouns drawn from the English Lexicon Project (Balota et al., 2007), with an average log frequency, word length, number of syllables, number of phonemes, and pronunciation response time of 7.14, 6.26, 1.76, 5.08, and 657 ms, respectively. Words were organized into triplets, and for a particular stimulus list, one word in the triplet was assigned to be the refreshed probe, the nonrefreshed probe, or the novel probe (if present; see Figure 1). To control for possible item effects between lists, each word served as the refreshed probe, the nonrefreshed probe, or the novel probe (when present) on different lists, for a total of nine stimulus lists that were rotated across participants. Each stimulus list included 48 instances of each condition (refreshed probe, nonrefreshed probe, novel probe), for a total of 144 trials. Within a list, conditions were equated across the word dimensions (i.e., frequency, number of syllables, etc.; all ps $> .8$). Conditions were randomly intermixed, and trials were presented in three separate blocks, with short breaks between blocks. Before the main task, participants performed a practice session that included 12 trials (4 instances of each trial type) with words that were not included in the main lists.

Recognition task. Test items included refreshed words, nonrefreshed words, and probe words from 50% of the trials seen during the main task. Each stimulus list from the main task was associated with two recognition lists that were rotated across participants. To construct the two recognition lists, words from half of each trial type in the main task were assigned to one recognition list, and words from the other half were assigned to the other recognition list. Trial position during the main task (i.e., whether it appeared early or late in the session) was balanced across the two lists. Each recognition list included 168 previously seen words and 168 new words (foils). Within each recognition list, word dimensions (frequency, word length, etc.) were similar for the word conditions (e.g., refreshed word, novel probe, etc.) and foils (all ps $> .8$). Because memory for all the words from a trial in the main task was tested, there were eight different conditions of test words (including foils) on the recognition test. If the test word had been refreshed during the main task, it could have appeared on a trial where the probe was the refreshed word (refreshed item—refreshed probe), the nonrefreshed word (refreshed item—nonrefreshed probe), or a novel word (refreshed item—novel probe). If the test word had appeared in the initial display but had not been refreshed, it could have appeared on a trial where

Table 1
Means and Standard Deviations of Demographic Information for Participants as a Function of Delay and Age Group

			Age			Education[a]		Verbal[b]		MMSE	
Age group	Delay	*N*	*M*	Range	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Young adults	100 ms	35	22	18–29	3.3	16	2.4	22	4.1		
	500 ms	34	22	18–29	3.2	16	2.1	20	5.8		
Older adults	100 ms	34	76	60–90	7.2	17	2.0	21	4.6	29	1.0
	500 ms	35	76	62–92	6.6	17	2.3	22	4.1	29	1.5
Younger-old	100 ms	16	70	60–74	3.9	16	2.0	21	4.9	29	0.6
	500 ms	14	69	62–73	3.1	17	2.4	21	4.8	29	1.4
Older-old	100 ms	18	81	75–90	4.8	17	1.9	22	4.4	29	1.2
	500 ms	21	80	75–92	4.6	17	2.2	23	3.5	28	1.5

Note. MMSE = Mini-Mental State Examination (Folstein et al., 1975); *SD* = standard deviation.
[a] Years of education missing from eight young adults in the 100-ms-delay group and nine young adults in the 500-ms-delay groups due to experimental error. [b] Verbal ability as indexed by an abbreviated version of the verbal subscale of the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1987).

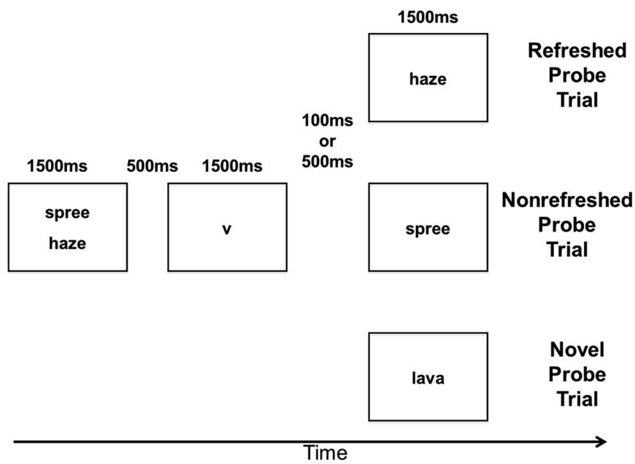

Figure 1. Sample stimuli and timing in the main task. Participants were presented with two words in a vertical column. After the words disappeared, participants were prompted to think of and say aloud the word that had just appeared in the location indicated by the arrow. After a variable (100-ms vs. 500-ms) delay, participants read aloud the probe word. The probe was either the word they had just refreshed (refreshed probe), the word they had just seen but not refreshed (nonrefreshed probe), or a new word (novel probe). Note that in the experiment, white stimuli were presented on a black background.

the probe was the refreshed word (nonrefreshed item—refreshed probe), the nonrefreshed word (nonrefreshed item—nonrefreshed probe), or a novel word (nonrefreshed item—novel probe). Additionally, the test word could have appeared in the main task as a novel word (novel probe) or not at all (foil).

Procedure

Main task. White stimuli were presented on a black background (see Figure 1). Each trial started with the presentation of two words, one above and one below center, for 1,500 ms. Participants were instructed to read these words silently to themselves. After a delay of 500 ms, during which the screen was blank, an upward- or downward-pointing arrow appeared in the center of the screen for 1,500 ms. Participants were instructed to think of the word that had just appeared in the location indicated by the arrow and to say this word aloud as quickly but as accurately as possible. After the arrow disappeared, the screen was blank for either 100 ms or 500 ms. After the delay, a word appeared in the center of the screen. This word was either the word from the initial display that the participants had just refreshed (refreshed probe trial), the word from the initial display that the participants had not refreshed (nonrefreshed probe trial), or a novel word (novel probe trial). Participants were instructed to read this word aloud as quickly but as accurately as possible. The intertrial interval was 3,000 ms.

During times when a verbal response from the participant was expected, the item on the screen (the word or arrow) turned green in color to indicate that their responses had been correctly recorded. This feedback allowed participants to monitor their volume to ensure accurate voice recordings.

Recognition task. After a short break (approximately 8 min), participants were administered a surprise long-term yes/no (with confidence) recognition memory test for the words that had appeared during the main task. On each trial, the question "Have you seen this word before?" was followed by a single test word. Participants used the index and middle fingers of both hands to press one of four buttons corresponding to four options: "definitely no," "maybe no," "maybe yes," and "definitely yes." The test word remained on the screen until the participant responded, and response accuracy was stressed above speed.

Apparatus

Stimuli for both the main task and recognition task were presented using E-Prime software on a PC laptop.

In the main task, verbal responses were measured using a free-standing microphone interfaced with the E-Prime voice key SRT box and were also recorded digitally. The digital recording was analyzed using a custom MATLAB script that identified sounds exceeding a specified amplitude and duration threshold and allowed a manual adjustment of the word onset if the automatic detection failed or was triggered early by nonspeech sounds.

In the recognition task, responses were collected via labeled buttons on the keyboard.

Results

Main-Task Response Times

Refresh response times. After the removal of trials in which there were participant errors (wrong word was refreshed, participants misspoke) or technical errors, the percentage of remaining trials was comparable in the 100-ms-delay (older adults [OA] = 95%, young adults [YA] = 98%, older-old = 96%, younger-old = 94%) and 500-ms-delay (OA = 95%, YA = 97%, older-old = 96%, younger-old = 95%) conditions.

Response times (RTs) to refresh (see Panel A in Table 2) were submitted to a 2 (Age: YA, OA) × 2 (Delay: 100 ms, 500 ms) analysis of variance (ANOVA). Older adults were significantly slower to refresh than young adults, $f(1, 134) = 74.40$, mean square error (MSE) = 8,291.52, $p < .001$, $\eta_p^2 = .36$. No other effects were significant. Subgroups of older participants were compared in a 2 (Age: Older-Old, Younger-Old) × 2

Table 2
Response Times to Refresh a Word as a Function of Delay and Age Group

	100-ms delay		500-ms delay	
Age group	*M*	*SE*	*M*	*SE*
A.				
Young adults	543	12	541	12
Older adults	681	20	670	16
B.				
Younger-old	659	33	655	24
Older-old	701	25	680	22

Note. *SE* = standard error.

(Delay: 100 ms, 500 ms) ANOVA (see Panel B of Table 2). Although RTs to refresh were 33 ms slower in the older-old compared to the younger-old participants, this difference was not significant, $f(1, 65) = 1.63$, $MSE = 11{,}687.88$, $p = .21$. The main effects of delay and the Delay × Age interaction were also not significant.

Probe response times. After the removal of trials in which there were participant errors or technical errors, the percentage of remaining trials was comparable in the 100-ms-delay (OA = 94%, YA = 97%, older-old = 96%, younger-old = 93%) and 500-ms-delay (OA = 94%, YA = 95%, older-old = 95%, younger-old = 94%) groups.

Probe RTs for all conditions are shown in Table 3. Novel probes were included to discourage uncued refreshing and are not of primary interest. However, it is worth noting that, as is clear from Table 3, both older and younger adults showed faster RTs on refreshed and nonrefreshed probes compared with novel probes, consistent with other findings of repetition priming on identification tasks (Fleischman & Gabrieli, 1998; but see Wiggs & Martin, 1994). Detailed analyses and data for novel probes are available from the first author.

To test our critical hypothesis that aging may delay inhibition of the refreshed word, we submitted probe RTs from refreshed and nonrefreshed trials to a 2 (Age: YA, OA) × 2 (Delay: 100 ms, 500 ms) × 2 (Probe: Refreshed Probe, Nonrefreshed Probe) ANOVA (Part A of Figure 2; Panel A of Table 3). There were significant main effects of probe, $f(1,134) = 21.29$, $MSE = 463.18$, $p < .001$, $\eta_p^2 = .14$, with longer response times to refreshed probes compared with nonrefreshed probes, and age, $f(1,134) = 26.07$, $MSE = 14{,}848.73$, $p < .001$, $\eta_p^2 = .16$, with longer response times in older adults compared with young adults. The predicted Age × Delay × Probe interaction was marginally significant, $f(1,134) = 3.13$, $MSE = 463.18$, $p = .07$, $\eta_p^2 = .02$. Young adults were slower to respond to refreshed compared with nonrefreshed probes at the 100-ms delay, $t(34) = 4.03$, $p < .001$, Cohen's $d = .68$, but not the 500-ms delay, $t(33) = 1.66$, $p = .11$. In contrast, older adults were slower to respond to refreshed compared with nonrefreshed probes at the 500-ms delay, $t(34) = 3.16$, $p < .01$, Cohen's $d = .53$, but not the 100-ms delay, $p = .34$. No other interactions were significant.

Panel B of Table 3 and Part B of Figure 2 show probe RTs separately for younger-old and older-old participants. Separate 2 (Age: OA, YA) × 2 (Delay: 100 ms, 500 ms) × 2 (Probe: Refreshed, Nonrefreshed) ANOVAs comparing young adults with each of the older subgroups found that the 3-way interaction was significant in the young versus older-old analysis, $f(1,104) = 5.11$, $MSE = 488.22$, $p = .026$, $\eta_p^2 = .05$, but not the young versus younger-old analysis ($p = .56$). Older-old participants showed no slowing to refreshed probes at the 100-ms delay ($p = .93$) and did show slowing at the 500-ms delay, $t(20) = 2.59$, $p = .017$, Cohen's $d = .57$. Younger-old participants were marginally slower to read refreshed compared with nonrefreshed probes at the 100-ms, $t(15) = 1.88$, $p = .08$, Cohen's $d = .47$, but not at the 500-ms delay, $t(13) = 1.78$, $p = .10$. In short, the older-old participants showed no evidence of inhibition until the 500-ms delay.

Long-Term Recognition Memory

Long-term recognition data were excluded for one older adult in the 500-ms-delay condition because of a large portion of missing data due to technical error. For old items, there were seven different conditions: words that had been refreshed during the main task on trials in which the probe word was the refreshed word (on refreshed probe trials), nonrefreshed word (on nonrefreshed probe trials), or a novel word (on novel probe trials); words that had appeared in the initial display but had not been refreshed (i.e., nonrefreshed words) on refreshed probe trials, nonrefreshed probe trials, and novel probe trials; and novel words from novel probe trials. For each of these seven conditions, old/new corrected recognition scores were calculated by subtracting the proportion of false alarms (foils to which participants responded "maybe yes" or "definitely yes") from hits (old items to which participants responded "maybe

Table 3
Response Times to Say the Probe Word Aloud in the Main Task as a Function of Trial Type, Delay, and Age Group

		Probe responses							
		Novel		Refreshed		Nonrefreshed		Refreshed–Nonrefreshed	
Age group	Delay	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
A.									
Young adults	100 ms	590	15	534	12	517	11	17	4
Older adults	100 ms	665	19	599	16	593	16	6	6
Young adults	500 ms	580	17	519	14	510	15	9	5
Older adults	500 ms	670	18	602	17	586	17	16	5
B.									
Younger-old	100 ms	645	24	585	18	572	19	13	7
Older-old	100 ms	684	28	611	26	612	24	−1	9
Younger-old	500 ms	650	29	571	25	559	23	12	7
Older-old	500 ms	684	22	622	22	604	23	19	7

Note. *SE* = standard error.

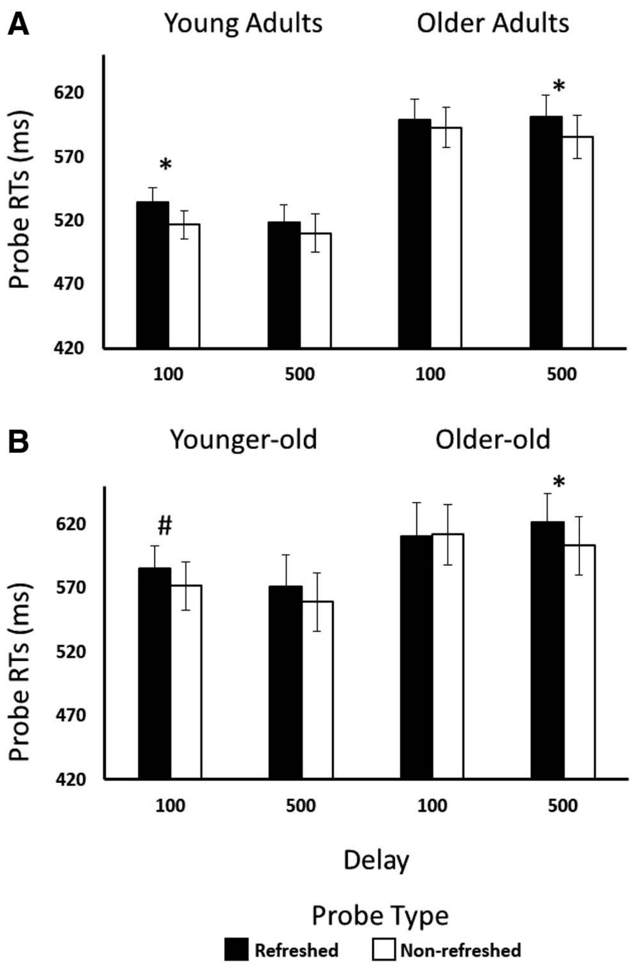

Figure 2. Response times to read refreshed and nonrefreshed probes as a function of delay and age group. Response times were significantly slower for refreshed compared with nonrefreshed probes at the 100-ms, but not the 500-ms, delay in young adults and in the 500-ms, but not the 100-ms, delay in older adults. Younger-old participants were marginally slower at the 100-ms, but not the 500-ms, delay, whereas older-old adults were significantly slower at the 500-ms delay but not the 100-ms delay. $^{*}p < .05$. $^{\#}p = .08$.

yes" or "definitely yes").[1] Data for all conditions are shown in Table 4.

Long-term memory for novel probes was not of primary interest here. It is worth noting that, as is clear from Table 4, long-term memory for a nonrefreshed item (that was not probed) was generally lower than that for a novel item. This makes sense because in both cases, the item was seen once, but the nonrefreshed item had shared attention with another item in the display, whereas the novel item had not; also, probed items were read aloud, whereas nonprobed nonrefreshed items were only read silently. As is clear from Table 4, refreshing largely made up for the shared attention deficit from a multiple-item display. Detailed analyses of the long-term memory results for novel items are available from the first author.

Young adults versus older adults. To examine the effect of refreshing a word on long-term memory, corrected recognition scores were submitted to a 2 (Age: YA, OA) × 2 (Delay: 100 ms, 500 ms) × 2 (Refresh: Refreshed, Nonrefreshed) × 2 (Probe: Probed, Nonprobed) ANOVA. Because there were no significant effects involving delay, the data in Part A of Figure 3 were collapsed across delay. There was a main effect of age, $f(1,133) = 29.17$, $MSE = .07$, $p < .001$, $\eta_p^2 = .18$, with higher recognition in young adults than older adults. There were main effects of refresh, $f(1,133) = 186.30$, $MSE = .01$, $p < .001$, $\eta_p^2 = .58$, and of probe, $f(1,133) = 272.07$, $MSE = .01$, $p < .001$, $\eta_p^2 = .67$, which were qualified by a significant Refresh × Probe interaction, $f(1,133) = 69.35$, $MSE = .01$, $p < .001$, $\eta_p^2 = .34$. The benefit of refreshing (refreshed word minus nonrefreshed word) was larger for nonprobed items than for probed.

Young versus younger-old adults. Focusing on younger-old adults, corrected recognition scores were submitted to a 2 (Age: YA, Younger-Old) × 2 (Delay: 100 ms, 500 ms) × 2 (Refresh: Refreshed, Nonrefreshed) × 2 (Probe: Probed, Nonprobed) ANOVA. Because there were no significant effects involving delay, the data in Part B of Figure 3 were collapsed across delay. There was a main effect of age, $f(1,95) = 16.31$, $MSE = .07$, $p < .001$, $\eta_p^2 = .15$, with higher recognition for young adults than for younger-old adults. The main effects of refresh, $f(1,95) = 125.07$, $MSE = .01$, $p < .001$, $\eta_p^2 = .57$, and probe, $f(1,95) = 162.02$, $MSE = .01$, $p < .001$, $\eta_p^2 = .63$, were qualified by a significant Refresh × Probe interaction, $f(1,95) = 51.06$, $MSE = .01$, $p < .001$, $\eta_p^2 = .35$. The refresh benefit was larger for nonprobed than probed items.

Young adults versus older-old adults. Focusing on older-old adults, corrected recognition scores were submitted to a 2 (Age: YA, Older-Old) × 2 (Delay: 100 ms, 500 ms) × 2 (Refresh: Refreshed, Nonrefreshed) × 2 (Probe: Probed, Nonprobed) ANOVA. Because there were no significant effects involving delay, the data in Part B of Figure 3 were collapsed across delay. The main effect of age, $f(1, 103) = 21.57$, $MSE = .07$, $p < .001$, $\eta_p^2 = .17$, showed that recognition scores were higher for young adults than for older-old adults. The main effects of refresh, $f(1, 103) = 133.08$, $MSE = .01$, $p < .001$, $\eta_p^2 = .56$, and probe, $f(1, 103) = 197.53$, $MSE = .01$, $p < .001$, $\eta_p^2 = .66$, were qualified by Refresh × Probe, $f(1, 103) = 39.78$, $MSE = .01$, $p < .001$, $\eta_p^2 = .28$, and Refresh × Probe × Age, $f(1, 103) = 5.16$, $MSE = .01$, $p = .03$, $\eta_p^2 = .05$, interactions. For probed items, young and older-old adult participants showed a similar refresh benefit ($p = .4$); for nonprobed items, the refresh benefit was larger in young than older-old participants, $t(105) = 2.4$, $p = .02$, Cohen's $d = .49$.[2]

[1] We also calculated memory ratings for each item, where "definitely yes" was scored as 4, "maybe yes" was scored as 3, "maybe no" was scored as 2, and "definitely no" was scored as 1. The pattern of results was similar to the corrected recognition presented here except where noted. Details of the memory ratings analyses are available from the first author.

[2] Memory ratings showed an additional Age × Delay × Refresh interaction, reflecting that for young adults, the refresh benefit was larger at the 100-ms delay than the 500-ms delay, whereas the older-old adults showed the reverse pattern—a larger refresh benefit at the 500-ms delay than the 100-ms delay.

Table 4
Corrected Recognition Scores for Each Word Type as a Function of Delay and Age Group

	100-ms delay						500-ms delay					
	On trials in which the probe was						On trials in which the probe was					
	Refreshed		Nonrefreshed		Novel		Refreshed		Nonrefreshed		Novel	
Condition	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
A. Young adults												
Words that were												
Refreshed	0.59	.03	0.54	.03	0.55	.03	0.59	.02	0.52	.03	0.51	.03
Nonrefreshed	0.33	.03	0.55	.03	0.33	.02	0.33	.03	0.55	.03	0.34	.02
Novel					0.57	.03					0.54	.03
Older adults												
Words that were												
Refreshed	0.43	.03	0.39	.03	0.34	.03	0.51	.02	0.44	.02	0.44	.03
Nonrefreshed	0.22	.02	0.39	.03	0.20	.02	0.26	.02	0.43	.03	0.30	.02
Novel					0.37	.03					0.42	.02
B. Younger-old adults												
Words that were												
Refreshed	0.45	.05	0.45	.05	0.36	.05	0.49	.03	0.40	.03	0.44	.03
Nonrefreshed	0.21	.02	0.42	.04	0.21	.03	0.22	.02	0.43	.04	0.29	.03
Novel					0.44	.05					0.39	.04
Older-old adults												
Words that were												
Refreshed	0.41	.04	0.34	.03	0.33	.03	0.52	.03	0.46	.04	0.44	.04
Nonrefreshed	0.23	.03	0.37	.04	0.19	.03	0.29	.04	0.42	.04	0.30	.03
Novel					0.31	.04					0.44	.03

Note. *SE* = standard error. □ indicates words that functioned as probes on those trials.

Discussion

The current study investigated whether older adults, like young adults, demonstrate reduced accessibility of an item that was just previously the target of reflective attention. Participants saw two words, then were cued to think of (i.e., refresh) one of them. After either a 100-ms or 500-ms delay, they saw and read aloud a probe word that was either the word from the initial display that they had refreshed (refreshed probe), the word from the initial display that they had not refreshed (nonrefreshed probe), or a new word (novel probe). Young adults showed longer response times to refreshed compared with nonrefreshed probes at the 100-ms delay, replicating our earlier finding (Johnson et al., 2013), but not at the 500-ms delay, thus demonstrating dissipation of refresh-induced inhibition within 500 ms in young adults. Of course, to fully characterize the timeline of refresh-induced inhibition, future research that parametrically varies the delay is needed.

In contrast to the young adults, refreshing resulted in reduced accessibility of the item in older adults at 500 ms but not at 100 ms. Interestingly, although the inhibitory effect emerged later in the older adults, it was of similar magnitude (a 17-ms slowing in YA at 100 ms and a 16-ms slowing in OA at 500 ms). That is, the timing, but not the degree, of inhibition differed between the age groups. Our post hoc examination of younger-old and older-old groups revealed that delayed inhibition may be particularly associated with advanced old age. Given that refresh RTs did not differ significantly between the younger-old and older-old participants, we cannot simply attribute the later emergence of inhibition in older-old participants to a slowing of refreshing—or, more precisely, at least not to the *initiation* of refreshing; it could be that older-old participants engage refreshing in a timely fashion but take longer to complete the process. Regardless, given the post hoc nature of this analysis, the relatively small samples in the younger-old and older-old subgroups, and the numerically (if not significantly) longer refresh RTs for older-old participants than younger-old, any conclusions regarding differences associated with different stages of aging are necessarily preliminary and suggest the need for further, systematic investigation of how both delay and age are related to deficits in inhibition. Also of interest, of course, would be whether inhibition deficits are related to the presence of subclinical histopathology in the brain that is associated with Alzheimer's disease but may appear in lesser degrees well before the emergence of any symptoms of dementia (e.g., Braak, Thal, Ghebremedhin, & Del Tredici, 2011).

What are the consequences of delayed inhibition of a just-refreshed item? Refreshing is the act of selectively focusing internal attention toward a single item, enhancing and/or prolonging the refreshed item's activation relative to other items that may be concurrently active (Johnson & Hirst, 1993). In this way, refreshing enhances the accessibility of the item for further cognitive processing (e.g., binding of the item to context, transforming or manipulating the item). However, some mechanism must act to allow attention to move to other potential

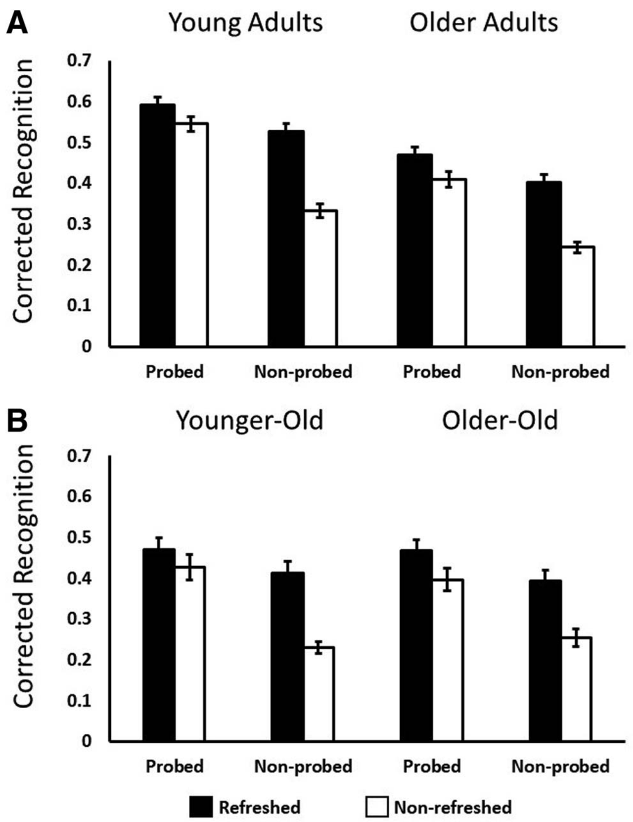

Figure 3. Corrected recognition on the long-term memory task for refreshed versus nonrefreshed and probed versus nonprobed items as a function of age group. The refresh benefit (refreshed compared with nonrefreshed words) was larger for nonprobed words than probed words in all age groups. Older-old participants showed a smaller refresh benefit for nonprobed items compared with young participants.

targets. We propose that the temporary refresh-induced inhibition observed in young adults is such a mechanism, allowing cognitive processing to not simply persist on a target that has been privileged by refreshing but to move toward new information (analogous to the biasing of perceptual attention to uncued locations in inhibition-of-return cuing tasks [Posner & Cohen, 1984], which emerges 300 ms later in older adults compared with young adults; e.g., Castel, Chasteen, Scialfa, & Pratt, 2003). Delayed inhibition of just-refreshed items could have a number of downstream consequences for older adults, for example, difficulty following a rapidly moving conversation due to interference from incompletely inhibited information that had been highlighted via refreshing. Similarly, in a working-memory task, older adults' working memory capacity could suffer due to the increased time required to shift reflective attention from one item to another, thus increasing the probability that other items in working memory will become inaccessible before becoming the target of refreshing or rehearsing.

If, as we propose, the function of inhibiting a just-refreshed item is to increase the fluidity of cognitive processing, it must, by necessity, be short-lived. That is, a prior target that was inhibited in order to allow reflective attention to move toward other items may become relevant again soon thereafter. Consistent with this idea, the inhibition observed at the 100-ms delay in young adults had dissipated by 500 ms. Additionally, the short-term inhibition of the refreshed probe did not prevent a long-term-memory benefit of refreshing, as evidenced by better long-term memory for refreshed compared with nonrefreshed items in young adults. Although our current paradigm does not allow us to determine at what point inhibition of the refreshed item (observed at the 500-ms delay) dissipates in older adults, the finding that older adults also showed a refresh benefit in long-term memory suggests that inhibition is also transient in this age group.

Further specifying the nature of the age-related inhibitory delay associated with refreshing remains an important task/goal. One possibility suggested by Johnson, McCarthy, Muller, Brudner, and Johnson (2015) based on their event-related potential results, in combination with previous fMRI findings (Raye et al., 2007), is that an experimental refresh task such as the one used here involves two cognitive subcomponents, potentially controlled by different regions of the prefrontal cortex (PFC): initiating refreshing (anterior PFC), followed by modulation of posterior representational regions (dorsolateral PFC). Although, as noted previously, we doubt that delayed initiation of the overall refresh process is a primary driver of the effects we observed, the possibility remains that the later modulatory aspects of refreshing are intact in aging but are slower to be deployed. The similarity in magnitude of the inhibitory effect between both age groups supports this possibility. However, the similarity in magnitude of inhibition is also consistent with the possibility that the deployment of inhibition is temporally preserved in aging, but the modulatory mechanisms are weaker in older adults and thus require more time to achieve a comparable suppression of representations. A third possibility is that the onset and/or strength of modulatory mechanisms are intact but take longer to complete in older adults because of stronger-than-normal activation of the to-be-suppressed item (i.e., the refreshed item). Future studies using a parametric variation of the postrefreshing delay may help to tease apart these possibilities by examining age differences in the timing and magnitude of the effect in young and older adults.

Our results are generally consistent with neurophysiological evidence of delayed inhibition in more complex working-memory tasks (Gazzaley et al., 2008; Jost et al., 2011; Yi & Friedman, 2014). Importantly, unlike other tasks that require some mix of perceptual and reflective attention, comparison of the contents of working memory to a perceptual cue, and/or rehearsal of multiple items across retention intervals of 900 ms or more, the current paradigm was designed to recruit a very simple act of reflective attention, that of refreshing a single item just experienced. Additionally, our participants were not told, and presumably were not specifically motivated, to actively inhibit the refreshed word. That is, participants showed inhibition in response to the probe, a part of the task in which they had to simply read aloud a word that was perceptually present, a task that is less likely to induce a conscious effort to inhibit the contents of working memory. Thus, the current findings demonstrate an age-related delay in inhibition of the perceptual processing of an item, resulting from a very recent, discrete, and simple act of reflective attention to the item.

Furthermore, the results address another fundamental question: What are the long-term effects of refresh-induced inhibition during encoding? First, in young adults in the 100-ms-delay group, we replicated the refresh benefit in long-term recognition memory that we found under the same conditions in our earlier study (Johnson et al., 2013). Second, we found that young adults also showed a similar refresh benefit at a longer (500-ms) probe delay. Third, older adults also showed a similar refresh benefit at both delays. This overall pattern provides further evidence that refreshing can have a positive impact on long-term memory. It is notable that the older-old participants showed a decreased long-term refresh benefit compared with young adults. Because older-old adults also showed the strongest evidence of a delay in refresh-induced inhibition, this suggests that a delay in inhibiting a refreshed word may contribute to deficits in long-term memory in aging. If so, it raises the interesting possibility that refresh-induced inhibition of an item might facilitate long-term memory for the refreshed item. That is, inhibiting an item may not only benefit other items, but it may also benefit the item itself.

It should be noted that older adults do not always demonstrate a long-term memory benefit for refreshed words (Johnson, Mitchell, Raye, & Greene, 2004; Johnson et al., 2002; Raye et al., 2008), and the impact of refreshing may depend on the nature of the items even in young adults (Johnson et al., 2005). It falls to future research to determine the circumstances (e.g., task expectations, type of information) under which refreshing does or does not benefit long-term memory and the circumstances affecting the long-term memory effects of inhibition associated with refreshing.

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